CEMENT AND LIME MANUFACTURE

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Modern Requirements of Cement.

An interesting article entitled "The Construction Industry's Demands from a Cement-Chemist's Viewpoint," by Dr. Gabriel Ashkenazi, is published in a recent number of *Pit and Quarry*, in the course of which the writer says he has sometimes felt puzzled when trying to satisfy the requirements of construction practice. Different factors play an important role in developing concrete properties and this fact has been strongly emphasised by the authorities on concrete. These factors, including climatic conditions, method of construction (rate, mixing, and placing), character of foundation and composition of the mixture, represent, strictly speaking, the external conditions which promote or hinder the development of the binding properties of cement.

Hardening.

The hardening process of cement presents a complicated phenomenon, the nature of which is still insufficiently explained. The opposed views fluctuate between the colloid and the crystal theory of hardening. The partisans of the colloid theory point out that the crystal theory is not consonant with the particular properties of set cement, and that the behaviour of concrete can be better understood and explained when accepting the colloid theory of hardening. Besides, the microscopic examination of set cement does not show the presence of crystals. Professor H. Kühl, who for many years sought to discover crystalline formations in thin sections of set cement, failed to achieve his object. Even twenty-year-old thin sections did not show any crystals.[1]. Many investigators, however, believe the process of setting and hardening to be the result of colloid and crystal formations. The recently published studies on the hydration of cement by Dr. Lennart Forsën indicate that the silicate compounds formed during this process are sub-

[1] Kühl (H.). *Cement Chemistry in Theory and Practice.* London. p. 34.

microcrystalline.[2] The fact that the first reaction of cement on hydration results in the formation of colloids is indisputable. This fact, however, does not exclude the possibility that in time the colloid mass may be converted into meta-colloidal, or even ultra-microcrystalline form, the presence of which is difficult to establish by means of simple microscopic examination.

Shrinkage.

From a practical point of view it may not be of great importance whether shrinkage is explained as the result of crystalline hydrate formation connected with a decrease of volume, or as the result of so-called " internal absorption," according to the colloid theory of hardening, or as the effect of both phenomena. Cement shrinkage lies in the nature of hydraulic hardening.

Gel is produced during the setting of cement and the density of this gel depends on its water content. The ability to imbibe varying amounts of water is a characteristic property of all gels. It has been proved that silica forms hydrogels containing as much as 330 mol. of water to 1 mol. of silica.[3] The amount of water can vary considerably, but it is obvious that cement-gels can hold a limited quantity of water. According to R. W. Carlson, " for a given gel there is an equilibrium water content and corresponding volume for each atmospheric humidity to which it may be exposed."

On the other hand, a colloidal state presupposes the minimum amount of water. A decrease of water below this minimum destroys the colloidal structure which cannot be re-established by the addition of more water. The cement gel, dried to such a point, cannot be revived. When such a desiccation occurs in the early stage of the hardening process, a weak gel is produced. The loss of water causes a considerable shrinkage and, as the weak gel structure cannot withstand the stress caused by this shrinkage, the concrete cracks. It is known that the cement grain hydrates gradually. It has been proved that the depth of penetration of water into a cement grain, surrounded by water during a period of 28 days, does not exceed a few thousandths of a millimetre.[4] The action of water on the surface of the cement grain produces a colloid mass ; subsequently the adjoined part of cement grain withdraws water from the primarily formed gel (internal absorption), producing new masses of gel. The gel complex contracts and its density increases, augmenting its elasticity as well as its resistance. Thus the normal shrinkage due to the normal hardening is harmless to concrete ; its rate corresponds to the quantity and quality of forming gel, and the internal stresses produced by this shrinkage are compensated by the stability and cohesion of the condensed colloidal cell.

The shrinkage of concrete and mortar is caused, however, not only by the normal contraction of the hardening gel. The often expressed view that the rate of shrinkage of mortar and concrete depends on the proportion of cement

[2] Forsén (L.). *The Chemistry of Accelerators and Retarders.* Paper presented at the international meeting on " The Chemistry of Cements," Stockholm, 1938.

[3] Van Bemmelen (J. M.). *Die Absorption.* Dresden, 1910, p. 201.

[4] *The Rate of Hydration of Cement Clinker.* Proceedings American Society for Testing Materials (1929), pt. 2, pp. 554–564.

are not quite correct. It has been shown, indeed, that the rate of shrinkage diminishes with the decrease of the content of cement, but this decrease has been far less than the reduced proportion of cement. Other factors influence the shrinkage of concrete, and under certain conditions their influence may become harmful to the durability of the construction ; for example, shrinkage due to the desiccation of the gel by the loss of its imbibed water to the air, as well as shrinkage due to thermal effects.

Generally, gel shrinks while drying and swells on wetting. This is true with respect to gelatine, for instance, which shows such a reversible course of volume change. As to the cement gel, this assertion cannot be accepted without reservation. If silica gel is dried enough, pores are formed and it loses its adsorptive ability.[5] It is possible that the drying out of silica gel changes its physical state from colloidal into sub-microcrystalline, and that this change lowers its ability to swell. The cement gel, composed chiefly of calcium hydrosilicates, is still less able to exhibit such a reversible reaction. R. W. Carlson showed that artificially dried 1½-in. to 12-in. bars of cement mortar, after a following treatment with water, not only regained the loss by shrinkage, but even increased their original length. The writer is of the opinion, however, that the regaining of lost volume observed by Carlson is due, not to the swelling of dried-out old gels, but to a new hydration of still unhydrated cement parts, which filled the pores of the dried-out mass with new colloid formations, a process similar to the phenomenon of self healing.

Heat of Hydration.

Very much attention has been given to the heat of hydration of cement. Heat of hydration is an inevitable phenomenon ; like shrinkage, it lies in the nature of hydraulic hardening. It represents chiefly the heat of hydration and solution of uncombined lime and gypsum and the heat of hydration of the proper constituents of cement. The presence of uncombined lime in a correctly prepared cement is excluded ; the hydrolysis of the proper constituents is the preliminary condition of hardening. Less heat of hydration means fewer hydration products, fewer colloidal matters, and a weak gel diluted with water.

Even for special construction, such as mass concrete, construction practice should not hesitate to use cement developing high strength at early ages. The writer prefers a lower content of high-strength cement to a higher content of a low-heat cement of poor strength. Heat of hydration is not the major factor affecting the thermal properties of concrete. The more important factors comprise the relation between the placing and stable temperatures, the methods of construction, and the exposure conditions. It is insufficient to reduce the heat of hydration ; it is far more important to create an easy way to remove the produced heat from the huge mass of concrete, because ultimately the temperature rise of concrete made of low-heat cement is not much lower than that of one

[5] Weiser (Harry B.). *Jellies and Gelatinous Precipitations.* Colloidal Behaviour, ed. by R. H. Bogue.

made of standard cement.[6] At the First International Congress for Concrete, M. E. Freyssinet stressed the fact that it is very difficult, if not impossible, to determine the correct coefficient of thermal expansion of concrete, pointing out that stresses generally ascribed to temperature changes are due to the changes in the hydrometric state of the air.

It is generally agreed that set mortars and concrete are capillary systems. According to Freyssinet,[7] concrete is a pseudo-solid substance, a material which seems externally to be solid, but in fact presents a network of interstices, more or less capillary, containing water or air. This net separates in many parts the really solid ingredients of concrete. Under the influence of different agents the interstices may be filled or emptied. For every constant temperature there exists an equilibrium depending upon the humidity. A complex of strength is produced directed from the exterior to the interior (shrinkage), the pressure of which may result in important deformations. A direct relation exists between the capillary diameters, the hydrometric state of the air, and the tension on the capillary walls, as well as between this capillary tension and the phenomena of shrinkage, plastic flow, and thermal expansion. Freyssinet's theory of concrete presents a remarkable attempt to explain and to link together many phenomena. This theory does not consider at all the gradual hydration of cement, and Freyssinet's explanation of shrinkage and creep as a result of variations in the pressure of water contained in the capillaries is open to serious objections.

The writer has attempted to show that it is often preposterous to correlate certain properties of cement, such as thermal expansion, heat of hydration, and shrinkage, to similar phenomena in concrete. Of course, these cement properties influence the behaviour of mortar and concrete, but this influence is usually exaggerated by the average structural engineer. It has been indicated that the natural contraction of cement gel in the process of hardening plays a relatively minor role in the movements in concrete. The heat generated by cement on hydration is far less important for the thermal effects in concrete than the other factors, such as the exposure conditions, methods of construction, and, in the case of mass concrete, the rate of the dissipation of heat.

Constitution of Cement.

Concrete engineers became accustomed to determining the expected properties of cement by taking into account the properties of individual compounds, such as C_3S, C_2S, C_3A, C_4AF, which assumedly comprise the most essential constituents of cement. Inasmuch as we do not possess a method for the direct estimation of the amount of these compounds in cement, their proportions are determined indirectly by the calculation from the oxides composition of cement, as given by its chemical analysis. In the opinion of the majority of engineers a certain amount of so established compounds, those of C_3S and, especially, C_3A, is undesirable and may be injurious for the construction. This opinion led to specifica-

[6] Savage (J. L.). *Special Cements for Mass Concrete.* (1936), p. 155.
[7] *Une Revolution dans la Technique du Beton,* 1936. Reviewed by P. Dumesnil. Revue des Materiaux de Construction (1937), Nov.

tions limiting the percentage of these computed compounds in cement. The writer was always opposed to such a regulation. Although the composition of Portland cement lies within certain limits, large fluctuations in the relationship of oxides are admissible. Strict general limitation to the contents of the principal oxides cannot be justified by the present state of knowledge. Even less is limiting the percentage of the computed compounds admissible, because the existence of some of these compounds in cement in the form of crystalline individuals is not sufficiently proved. Apart from this consideration, the behaviour of the laboratory-prepared pure crystalline compounds gives us no right to assume that they will behave in the same way in a complex combination such as Portland cement. Besides, it has been established that these compounds exist in commercial cements, not in the form of crystalline individuals, but partly in the state of solid solutions. Further, the presence of tricalcium-aluminate, even in cases where, according to the usual methods of calculation, its percentage was sufficient to be experimentally established, could not be detected either by means of the metallographic method,[8] or by petrographic examinations.[9] In spite of these facts the tendency towards limiting certain computed compounds still exists in this country. This tendency is unconsonant with the results of theoretical researches, as well as with industrial practice. The writer has produced excellent cements with a content of more than 10 per cent. of computed C_3A and very poor cements whose contents of this compound were less than 7 per cent. [The proportions of other computed compounds, except C_4AF, of course, as well as the manufacturing conditions were practically unchanged.] The most favourable composition ultimately depends on the nature of the raw materials and the manufacturing conditions only. Specifications leading to vigorous regulation of the composition of cement are handicapping the normal course of manufacture. It is, however, necessary, and within the rights of customers, to specify the general properties of cement, such as the resistance, setting time, heat of hydration, soundness, shrinkage, etc. Requirements connected with the chemical composition, especially those limiting the proportions of "computed compounds," are inadmissible. The producer himself will determine the right way and the suitable mixture in order to make a product having the required properties.

[8] Insley (H.). National Bureau of Standards, Journal of Research (1936), pp. 353–361.
[9] Brown (Levi S.). Proceedings Amer. Society for Testing Materials, v. 37, pt. 2, pp. 277–305.

Honour for Professor Forsën.

A Polhem medal (a medal instituted in memory of the 17th-century Swedish inventor, Christoffer Polhem, for prominent scientific workers) has been awarded by the Swedish Association of Engineers to Professor Lennart Forsën, for his thesis "On the Chemical Reactions in the Hardening of Cement," presented at the Symposium on the Chemistry of Cements, held in Stockholm in 1938.

Refining Raw Materials by Flotation.

A CEMENT works designed with a view to the use of the froth flotation process is described in a recent number of the Cement Mill edition of our United States contemporary *Concrete*. This works is in the Argentine, and has been in operation for eighteen months. It was built for the Compania Argentina de Cemento Portland, and is located at the town of Parana about 200 miles north of Buenos Aires. The raw materials available are unsuitable for the production of cement of high quality, for the reason that the lime content is too low and the silica content too high. By the flotation process the raw materials can be so refined and controlled that Portland cement of the highest quality can be made, and, in addition, it is possible to meet the requirements for modified cements, including low-heat and sulphate-resisting cements, by making relatively simple adjustments.

The deposit is described as a consolidated marl. The overburden is clay, having a silica content of about 68 per cent.; it could, however, be used if a small percentage of the silica were removed. Following the clay is a stratum of a soft lime-bearing deposit known as soft *tosca*, having a silica content of about 66 per cent., and about 5 per cent. of calcium carbonate. Next is a stratum of a somewhat similar but harder material, known as hard *tosca*, having a silica content of about 20 per cent. but with a content of calcium carbonate of about 72 per cent. Below the hard *tosca* is a crystalline limestone known as *piedra* (stone) with a high content of calcium carbonate (about 90 per cent.) and a silica content just under 10 per cent. The silica content in the several strata is misleading, for the reason that it occurs mainly in the form of quartz. In the lowest stratum—the *piedra*, or crystalline limestone—this quartz is in the form of coarse particles. In the hard *tosca* it appears largely as coarse quartz grains. In the soft *tosca*, which is used as the source of clay, the silica also occurs mainly in the form of coarse quartz grains.

Essentially the function of the flotation process is that of recovering the calcium carbonate and the fine clay materials, and removing and discarding much of the silica. Through the processing operation it is also necessary to control the proportion of alumina so as to aid in bringing about the necessary mixture for low-heat and sulphate-resisting cements.

Fig. 1 shows the interior of the cell-house, where the flotation process takes place. The equipment of the cell-house consists mainly of a turbo-mixer, which serves as a surge tank and also as a storage tank; an agitated feed tank; and ten 56-in. flotation cells which recover the calcium carbonate and remove the excess quartz and alumina. The function of these flotation cells is primarily that of performing the three steps of "roughing," "scavenging," and "cleaning." The cell feed passes from the turbo-mixer to the agitated feed tank, which in turn delivers the feed to the first of four "rougher" cells connected in series and seen as the centre row in the illustration. The tailings from these cells are fed to the first of the four "scavenger" cells, also connected in series, and shown at the

right in the illustration. The "scavenger" concentrates are of relatively low grade and are, therefore, fed to the first of two "cleaner" cells, connected in series and shown at the far left and towards the rear in the illustration. The tailings of the last "scavenger" cell are the final "rejects" and are pumped to waste.

Control of the flotation is effected mainly by means of calcite-collecting reagents fed into each cell of the flotation circuit. Each of the cells is equipped with an adjustable feeder that controls the rate of feed of the reagent. An effective reagent for this purpose—the kind used at the Argentina plant—is known as Cyanamid 608, and was developed jointly by the Separation Process Company

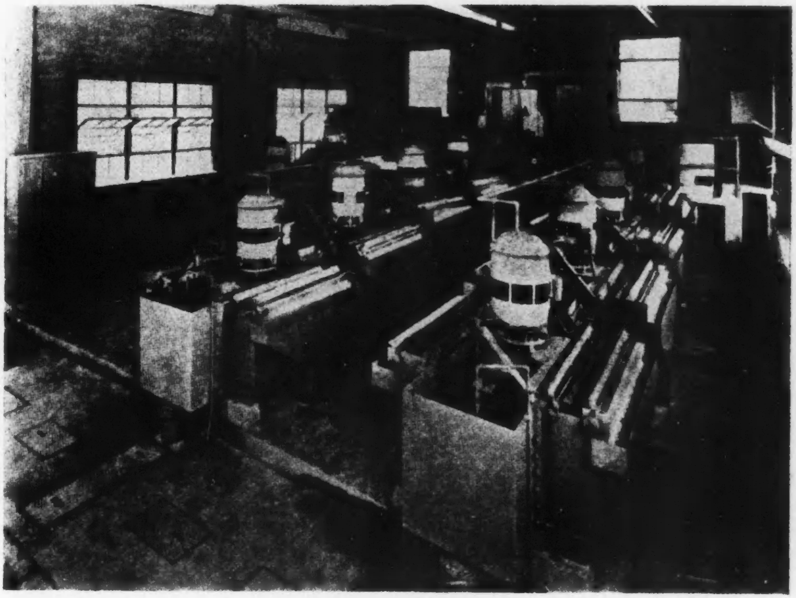


Fig. 1.—Froth Flotation Plant.

and by the American Cyanamid Company. This reagent has given wholly satisfactory service. In this connection it is interesting to consider a discussion of reagents in a report issued by the U. S. Bureau of Mines (R. I. 3473, October, 1939). On page 35 of this report is a quotation from another Bureau of Mines report which concludes, in part, that "experimenters spend too much time seeking new flotation reagents that will give a more selective filming, when actually their troubles are due rather to impurities that either mask the true mineral surface or act as activators on surfaces of minerals that are not to be floated."

Glass in Portland Cement Clinker.

THE following is from the *Technical News Bulletin* of the United States Bureau of Standards:

In the *Journal of Research* (N.B.S. 21, 355 (1938) RP1135) a method was described for determining quantitatively the constituents in Portland cement clinker by the microscopic analysis of polished surfaces of clinker after etching with suitable reagents. The results of the quantitative microscopic analyses of a number of samples of commercial Portland cement clinkers were compared with the results obtained by the calculation of constituents from chemical analysis. For a few of these samples the values for glass obtained microscopically were compared with the values found by an independent method involving the heat of solution of the clinkers (*Journal of Research*, N.B.S. 20, 77 (1938) RP1066). It was found that the values for "light interstitial" material obtained microscopically were, for many samples, considerably in excess of those for $4CaO.Al_2O_3.Fe_2O_3$ calculated from the chemical composition, whereas the values for glass obtained microscopically were less than those found by the heat-of-solution method. It was concluded in RP1135 that the "light interstitial" material was a single phase, because none of the etching reagents used caused any differentiation of this material.

Since the publication of RP1135 renewed effort has been made to find reasons for the discrepancies between the results of the microscopic analysis and the results of the other methods used. This has led to a search for reagents that might attack the "light interstitial" material. A reagent recommended by Tavasci (*Giorn. Chim. Ind. Applicata* 16, 538 (1934)) composed of 4 parts of 10 per cent. NaOH and 1 part of 10 per cent. $Na_2H\ PO_4$ and used at 50 deg. C. is found to attack all the interstitial material and therefore is not suitable for differentiation.

Further search has shown that strongly alkaline solutions under carefully controlled conditions of time, temperature, and concentration etch portions of the "light interstitial" material. The most satisfactory reagent found is a 10 per cent. solution of KOH. The polished specimen is agitated in this solution for 15 seconds at a temperature of 29 deg. C. Microscopic examination of polished thin sections of clinker etched with the alkaline solution show definitely that the etched portions of the "light interstitial" material contain isotropic material with a high index of refraction and a dark-green colour, whereas the unetched portions are distinctly birefringent, with high indexes of refraction and frequently strong pleochroism. It is assumed from the optical properties that the etched material is a glass containing a high percentage of iron, and that the unetched material is essentially the crystalline compound

$$4CaO.Al_2O_3.Fe_2O_3.$$

The clinker specimens analysed microscopically in RP1135 have been re-analysed after etching with the new reagent. The results are to appear in a

forthcoming paper together with a more detailed description of the etching process and photomicrographs showing the effects of the reagent on the polished specimens. In general, the re-analysis gives lower values for " light interstitial " material and higher results for glass than the first microscopic analysis. The values for glass are more nearly in agreement with the values found by the heat-of-solution method.

Concreting in Cold Weather.

USE OF ALUMINOUS CEMENT.

During the cold weather of January last a reinforced concrete structure, which which was a part of a large building scheme, was urgently required for the installation of machinery. The building measures 57 ft. by 52 ft. by 28 ft. high ; the walls are 12 in. thick, and the flat roof is of the beam and slab type with a maximum span of 40 ft. The concreting of the foundations and floors was carried out to schedule in December last, but at the beginning of January severe cold set in and lasted for nearly a month, during which period the temperature never rose above freezing point, the maximum and minimum temperatures being 29 deg. F. and 14 deg. F. respectively. All ordinary concreting was stopped, but it was decided to proceed with this structure, using aluminous cement and relying on the heat generated by the cement to enable the concrete to harden. Concreting with aluminous cement commenced at ground level on January 3 and the walls, beams, and floor slab were completed by January 19.

Some difficulty was experienced in preventing the aggregates from freezing as no steam was available ; a ring of coke braziers was therefore kept alight day and night around the heaps of aggregates. Great care was taken that no frozen aggregate was placed in the mixers.

Steel forms were used, and these were particularly useful as they did not absorb any water from the concrete. A lift of 3 ft. a day all round the walls was maintained. Due to the confinement of the concrete in the forms, and its consequent rapid rise in temperature, it was not necessary to cover the outside of the forms with any protective material, and no difficulty was experienced in preventing the mix from freezing during the three or four hours before the chemical generation of heat in the concrete took place.

Wall forms were struck twenty-four hours after the concrete was placed ; the only reason they were not struck earlier was shortage of labour.

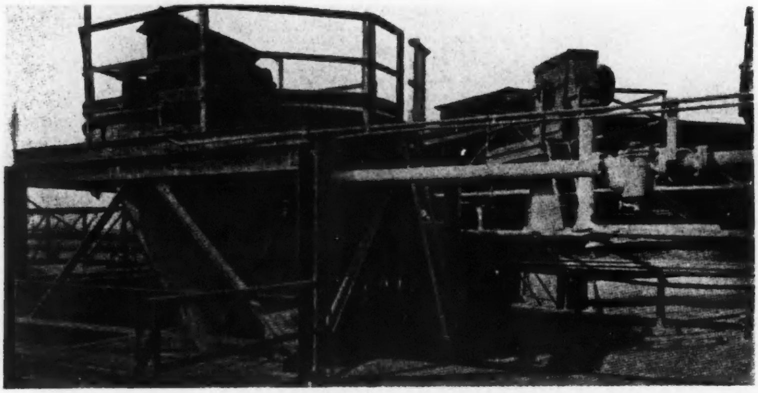
The roof slabs and beams were cast in two days and the shuttering struck on the third day. The heat generated by the aluminous cement was always sufficient to prevent the curing water from freezing. The concrete was handled by labourers without special experience, the only precaution taken being insistence on careful washing out of the mixers at the end of each day's work.

[A description of concreting successfully carried out at a temperature of zero Fahr. with the use of aluminous cement was given in our last issue.]

Cooling Portland Cement

A METHOD of reducing finished cement temperatures from 200 deg. F. to 140 deg. F. in bulk handling with a cone-shaped cooler by means of flowing water is described in a recent number of *Rock Products* by M. Bror Nordberg, from whose article the following is taken.

Finished cement temperatures are usually in the neighbourhood of 200 deg. F. when taken in bulk from the stockhouse of the Louisville Cement Co. For ordinary weather conditions this temperature causes no inconvenience, but during summer months difficulty is experienced by labourers in handling the cement from trucks.



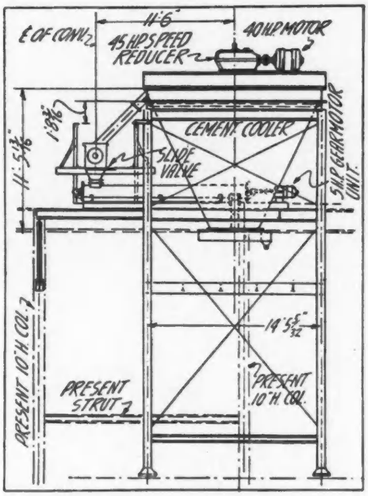
Cooler installed to receive Cement directly from the Mills by Screw Conveyor. Note Inlet Pipes at the Bottom Foreground for the Introduction of Compressed Air into Pneumatic Feeder. Main Screw Conveyor to the right.

The Company installed a cement cooler in the year 1938 which reduced the temperature by 50 to 60 deg., and in future it is proposed to cool all cement manufactured from May to September.

The cooler, which was manufactured by Messrs. F. L. Smidth & Co., is the first of its type installed in a United States cement plant. It comprises an inverted steel cone through which cement is introduced at the bottom and is then passed in a thin film along the inner face of the outside steel plate to discharge at the top. A continuous film of water moving over the outside of the cone takes up the heat passing through the shell. Within the cone is an agitating device consisting of a vertical shaft carrying agitator arms which are interconnected by flights parallel to the sides of the tank. The rotation of the agitating device, at 90 to 100 revolutions per minute, creates centrifugal force and suction causing the cement to be conveyed upward in a thin layer next to the tank wall to discharge at the top. It is necessary that the cement be

uniformly fed to the cooler in a fluffy state if the agitator scrapers are to operate effectively.

The cooler has 270 sq. ft. capacity, and is placed between the clinker grinding building and the stockhouse adjacent to a 16-in. screw conveyor carrying the finished cement. From the screw conveyor housing an adjustable slide valve releases any desired part of the cement stream into a pneumatic feeder serving the cooler, and the cooled cement returns into the same conveyor to blend with the cement not cooled. The 12-in. pneumatic feeder which receives the cement from the main screw conveyor is a horizontal chamber into which air is introduced for its entire length at regular intervals with blades rotated intermittently to keep the material agitated. Air is introduced at 10 lb. per sq. in. at the rate of 10 cu. ft. per minute to create fluidity. The feeder shaft is driven by a 5 h.p.,



Elevation of Cement Cooler.

44 r.p.m. gear-motor unit through a flexible coupling, and the agitator within the tank is driven at 90 to 100 r.p.m. by a 40 h.p. motor through a vertical speed reducer. At this speed the cement film next to the tank housing is about $1\frac{1}{2}$ in. thick.

Water at 80 to 90 deg. F. is used for cooling. The water is pumped into a 5-in. diameter pipeline encircling the top of the cooler, and is released continuously at 5 lb. per sq. in. through $\frac{3}{32}$-in. diameter holes to the cooler surface. When the cooler plate is free from scale, a continuous bath of water runs down the outside to the bottom where it is trapped and run to waste. The pump handles about 4,000 gal. of water per hour in normal operation. It is dust-tight and requires no labour other than the removal of lime deposit and surface scale from the outside wall. This deposition is removed about once in five months by the use of wire brushes.

The plant has a rated capacity of 5,000 to 6,000 barrels of standard Portland cement in 24 hours, and also manufactures high-early-strength cement. Kilns are equipped with heat recuperators and the clinker is stored and reclaimed for grinding in straight tube mills without air separators. The maximum temperature of the clinker introduced into the mills is about 190 deg. F. The mills are water-sprayed and the average temperature of the standard cement is 200 to 225 deg. F. when entering the finished cement screw conveyor.

Before entering the cooler the average temperature is 203 deg. F. and at the bins it is 154 deg. F. While readings were being taken, 1,850 barrels of cement were placed in one bin in 10½ hours. About 130 barrels per hour were put through the cooler and the remainder by-passed, with the cooled cement stream, joining the remainder in the screw conveyor. The cooling water, at 80 to 90 deg. F., was heated 25 to 28 deg. F. In manufacturing high-early-strength cement, the higher temperature of the cement entering the cooler is offset by requiring the passage of considerably less material, so that the final temperature of the cement entering the bins is about the same as that of standard cement. About 160 deg. F. is considered a favourable cement temperature for handling in the hot months.

Ball-Mill Grinding.*

Relation of Particle Size and Power.—The influence that particle size may have on power is illustrated in *Table* 5. There the variation in comminution was moderate but the power varied by almost 10 per cent. For this information five batch tests were run with durations of 2½, 5, 10, 15, and 20 minutes respectively. The first column of size analyses shows the mean of two products—the feed at the beginning and the product after 2½ minutes; it was derived by taking arithmetical averages, sieve by sieve. For the second column the size analyses for the 2½-minute and the 5-minute tests were similarly averaged. This method was carried through so that the last column shows the size analysis that could be expected if the 15-minute to 20-minute period were half-finished; that

TABLE 5.—Effect of Particle Size on Power.

(Mill, cylindrical, 19 by 36 inches. Circuit, batch. Speed, 60 per cent. critical. Ball load, Davis No. 1. Weight, 796 lb. Volume, 45 per cent. Ore charge, chert, 100 lb. Consistency, 60 per cent. solids.)

Size, mesh	Feed, weight percent	Mean sizing analyses of charge in mill, weight percent: Time period in minutes				
		0.0–2.5	2.5–5	5–10	10–15	15–20
8	1.7	1.1	0.4	0.1	....	....
10	25.2	18.7	9.0	3.3	0.5	0.1
14	55.0	45.1	28.3	13.5	3.2	.5
20	76.7	66.8	49.8	30.7	11.5	2.6
28	87.2	79.5	65.5	47.5	26.1	10.7
35	93.4	87.8	77.5	63.6	45.3	28.3
48	96.2	91.9	83.9	73.0	58.3	43.8
65	97.9	94.7	88.6	80.4	69.3	58.1
100	98.9	96.4	91.8	85.5	77.0	68.2
150	99.4	97.4	93.9	89.0	82.6	75.8
200	99.6	98.1	95.2	91.3	86.2	80.7
−200	4	1.9	4.8	8.7	13.8	19.3
Horsepower, by periods	....	1.337	1.307	1.264	1.234	1.226

is, the size analysis is what could be expected if the test had been stopped at 17½ minutes.

In the first test about half of the product was on a 14-mesh sieve, and in the last test about the same amount was on a 48-mesh sieve. Power was highest during the first period, indicating that the coarser particle sizes keyed the balls more than the finer particles. The investigation was not carried far enough to use coarser ore and determine what size had the maximum keying effect. The speed, being only 60 per cent. of critical, was slow enough for the keying to affect the power curve as noted. If the speed had been high the power curve might have been at its peak in the last tests. Then the effect of the coarser grains would have been to key the balls as before and cause them to be cataracted so high that the power would have been reduced; that is, they would have impinged above the 8 o'clock position. Hence, the accompanying variables must be taken into account in each investigation.

* Continued from April number.

Pulp Consistency.—Batch grinding affords the best opportunity for first studies of pulp consistency. *Table* 6 shows some of the results. The consistencies ranged from 80 to 20 per cent. solids. The initial five tests will be considered first and the last one will be mentioned later. In the last test of the series of five (33 per cent. solids) so much water was used that the mill was filled. The thickest pulp required the most power; but it is unsafe to make so broad a generalisation. This order would have been reversed at a high speed; for example, if the speed had been on the right side of the high point in the power curve, indicated by the heavy line at the bottom of *Fig.* 2, the balls in the thin pulp would have impinged nearer the 8 o'clock position than those in the thick pulp; the balls in the thick pulp would have impinged so high that the results

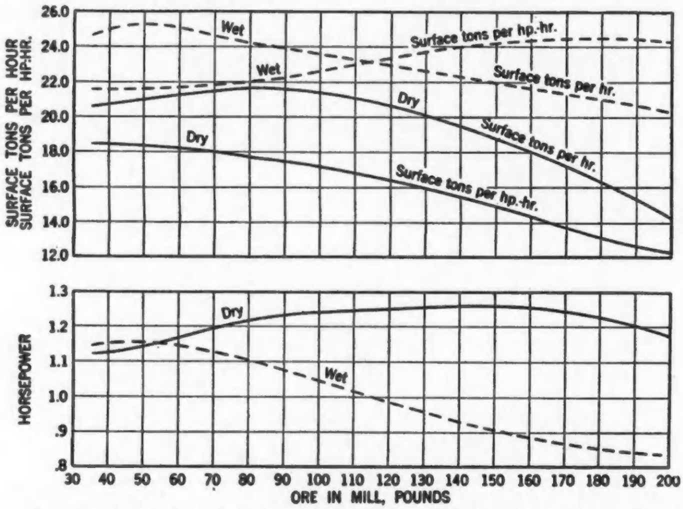


Fig. 1.—Comparison of wet and dry grinding. Batch tests, chert, 50 per cent. critical speed. Wet grinding at 60 per cent. pulp consistency.

would have been as if the speed were at about 95 per cent. critical in the above-mentioned figure.

The capacity and power decreased steadily as more water was used. The efficiency, which is the amount of grinding divided by the power, was highest with the thinnest pulp. The thinnest pulp (33 per cent. solids) was favourable to the best selective grinding, as shown by the cumulated per cent. weight on a 14-mesh or 20-mesh sieve. This is natural because so much water held the fines in suspension and left the coarse particles to be subjected to the ball action in the lower part of the mill. Although the load of water was heavy, its weight was somewhat counterbalanced because the mill was filled.

The last test—with 20 per cent. solids—had to be specially arranged because a charge with 33 per cent. solids filled the mill. To have a pulp as dilute as 20 per cent. solids, the ball load was drawn down to 30 per cent. volume and the

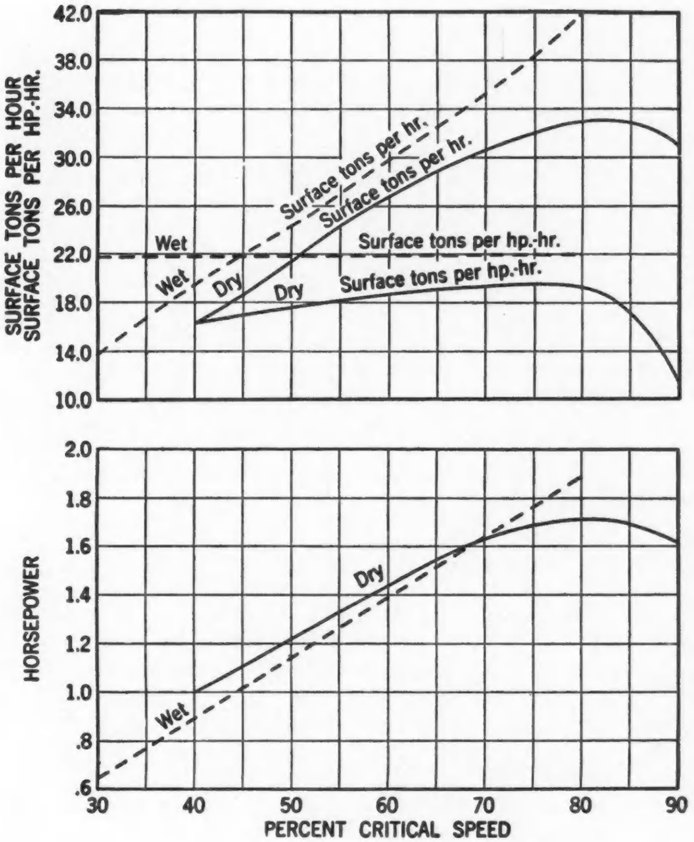


Fig. 2.—Comparison of wet and dry grinding at various speeds. Batch tests, 75 lb. chert. Wet grinding at 60 per cent. pulp consistency.

TABLE 6.—EFFECT OF PULP CONSISTENCY IN BATCH GRINDING.

(Mill, cylindrical, 19 by 36 inches. Circuit, batch. Speed, 40 per cent. critical. Ball load, Davis No. 1. Volume, 45 and 30 per cent. Ore charge, chert, 100 and 67 lb. Consistency, varied.)

Size, mesh	Feed, weight percent	Product, percent solids					
		80	70	60	40	33	20
8	1.7	0.4	----	----	----	----	----
10	25.2	6.8	3.2	0.8	0.4	0.4	0.4
14	55.0	20.1	10.5	4.0	3.1	2.6	2.7
20	76.7	35.5	23.6	13.8	12.1	10.2	10.8
28	87.2	48.8	38.0	28.8	27.7	25.2	26.5
35	93.4	59.2	52.9	46.9	46.8	42.3	44.0
48	96.2	67.7	63.1	59.4	59.8	57.4	59.0
65	97.9	74.2	71.5	69.8	70.4	68.5	69.7
100	98.9	80.0	77.8	77.2	77.9	77.3	78.3
150	99.4	83.8	82.5	82.6	83.3	82.8	83.5
200	99.6	86.8	85.9	86.2	86.8	86.4	87.0
−200	.4	13.2	14.1	13.8	13.2	13.6	13.0
Surface tons per hour	----	20.0	19.9	18.1	15.8	16.5	15.6
Surface tons per horsepower-hour	----	20.0	21.8	22.0	23.0	24.2	23.8
Ton per hour	----	.192	.172	.15	.133	.133	.13
Horsepower	----	.95	.91	.82	.69	.68	.65
Ton per horsepower-hour	----	.202	.193	.182	.194	.195	.199
Time, minutes	----	15.6	17.0	20.0	22.6	22.5	15.4

TABLE 7.—OPEN CIRCUIT FOR CAPACITY AND EFFICIENCY AT DIFFERENT PULP CONSISTENCIES.

(Mill, cylindrical, 19 by 36 inches. Circuit, continuous, open. Discharge, 4 inches. Speed, 50 per cent. critical. Ball load, Davis No. 2. Volume, 45 per cent. Ore charge, chert. Consistency, varied.)

Size, mesh	Feed, weight percent	Product, percent solids				
		64	54	43	25	10
8	1.7	----	----	----	----	----
10	25.2	1.3	1.0	1.2	1.7	3.5
14	55.0	4.9	3.7	4.4	5.9	11.2
20	76.7	11.8	8.9	9.9	13.0	22.8
28	87.2	22.7	17.6	18.9	23.3	36.4
35	93.4	36.3	29.8	30.8	36.0	49.8
48	96.2	49.8	43.7	44.6	49.4	61.9
65	97.9	60.7	56.0	56.9	61.0	71.3
100	98.9	70.4	67.3	68.3	71.7	79.4
150	99.4	76.7	74.7	75.7	78.5	84.5
200	99.6	81.4	80.0	81.0	83.3	87.9
−200	.4	18.6	20.0	19.0	16.7	12.1
Surface tons per hour	----	21.7	23.8	23.1	20.8	15.5
Surface tons per horsepower-hour	----	21.6	23.8	23.1	20.8	15.6
Ton per hour	----	.143	.143	.143	.143	.143
Horsepower	----	1.01	1.00	1.00	1.00	.99
Ton per horsepower-hour	----	.142	.143	.143	.143	.144

ore charge proportionately reduced. Water was then added to fill the mill. The results of grinding were much like those with 33 per cent. solids. All in all, 33 per cent. solids was the best for efficiency and selective grinding. The selective grinding was far better than in the case of the 80 per cent. pulp; with 33 per cent. solids only 10·2 per cent. of the ore remained on the 20-mesh sieve, whereas with 80 per cent. solids 35·5 per cent. remained on the same screen. As some operators prefer a thick pulp, the additional capacity gained by the thick pulp warrants consideration. When they have found that the capacity is best with a thick pulp, they may obtain the same advantage with a dilute pulp by increasing the speed of the mill. The best efficiency and selective grinding was at 33 per cent. solids; of course, so much water could not be held in the mill when the circuit was open.

Open-circuit Grinding.—The effect of pulp consistency may be examined further in *Table* 7, which shows open-circuit grinding. The pulp consistencies of the feed ranged from 10 to 64 per cent. solids. A thicker pulp could not be handled by the feed scoop. The horsepower was about the same in each test, and since the feed rate was always the same the number of tons per horsepower-hour was constant throughout. Having established this constant, the diagnosis may be made quickly without surface calculations. In fact, surface calculations make a rather rough criterion when there is so much difference in the amount of the minus 200-mesh size, as is shown in *Table* 7. However, there is no doubt that in accordance with the calculations the best capacity and efficiency occurred with 54 per cent. solids, and an impartial examination will show that the selective grinding was about the same throughout. An ore of different particle size would have required a different pulp consistency for best work. *Tables* 6 and 7 cannot be compared advantageously because ball loads and speeds were not the same.

In *Table* 6 it was shown that the batch mill could hold only enough water to reduce the pulp consistency to 33 per cent. What, then, was the condition in the mill with a continuous feed and discharge as dilute as 10 per cent. solids, and was the pulp in the mill of the same consistency as the effluent? When the feed was very dilute a part of the ore was sluiced out of the mill and replaced by water, so that the percentage of solids in the mill was about the same as the feed and effluent. The mill with 10 per cent. solids contained only 17 lb. of ore, whereas with a normal pulp it would have contained 75 lb. or 100 lb. By these tests the pulp consistency in the mill in continuous work seems to be the same as the effluent.

Rod Mills with Different Discharge Openings: Various Speeds.—In a study of rod-mill discharge openings of different sizes, four pairs of tests were made at speeds of 40, 50, 60, and 70 per cent. of critical. In each pair the discharge openings were 8 in. and 4½ in. respectively. The tests were conducted so that the tons per horse-power-hour were nearly the same. This manner of conducting the tests gave about the same amount of subsieve size in each. The results are shown in *Table* 8. The similarity of the size analyses is notable. At 70 per cent. speed and with 8-in. discharge the capacity was less than in the

analogous test at 60 per cent. speed, and the power was increased so much that efficiency was noticeably impaired. A similar comparison of the work with the 4½-in. discharge at 70 per cent. speed shows some advance in capacity over 60 per cent. speed ; but, again, the power was increased so much that efficiency declined. A general examination leads to the conclusion that 70 per cent. speed is too high. With the large discharge the power was higher. This principle is well known, but here the measure of the difference in power is given. It was only about 2 per cent. The best capacity and efficiency were with the large discharge.

TABLE 8.—ROD-MILL PERFORMANCE AT DIFFERENT SPEEDS AND WITH DIFFERENT DISCHARGE OPENINGS.

(Mill, cylindrical, 19 by 36 inches. Circuit, continuous, open. Discharge, varied. Speed, varied. Load, rods, 1¼ inch. Weight, 1,020 lb. Volume, 45 per cent. Ore charge, chert. Consistency, 60 per cent. solids.)

Size, mesh	Feed, weight per-cent	Percent critical speed							
		40		50		60		70	
		Discharge opening, inches		Discharge opening, inches		Discharge opening, inches		Discharge opening, inches	
		8	4.5	8	4.5	8	4.5	8	4.5
8	1.7	-------	-------	-------	-------	-------	-------	-------	-------
10	25.2	-------	0.2	-------	0.1	-------	0.4	0.3	0.7
14	55.0	2.4	4.8	3.2	3.0	3.5	5.1	6.2	7.6
20	76.7	14.7	22.1	19.4	16.5	18.9	21.8	25.4	27.5
28	87.2	33.0	41.1	38.1	35.5	37.6	40.3	43.5	45.5
35	93.4	51.8	57.8	55.7	54.0	54.7	57.0	59.4	61.2
48	96.2	63.1	67.6	66.2	65.0	65.2	67.3	69.1	70.3
65	97.9	72.1	75.3	74.5	73.7	73.5	75.4	76.8	77.4
100	98.9	78.6	80.9	80.4	80.0	79.7	81.4	82.5	82.5
150	99.4	83.4	85.2	84.7	84.6	84.2	85.9	86.7	86.5
200	99.6	86.5	87.9	87.4	87.6	87.2	88.8	89.4	89.1
−200	.4	13.5	12.1	12.6	12.4	12.8	11.2	10.6	10.9
Surface tons per hour		21.3	18.5	26.2	25.2	33.1	30.0	32.7	32.5
Surface tons per horsepower-hour		19.7	17.5	19.1	18.9	20.0	18.4	17.0	17.1
Ton per hour		.187	.184	.251	.236	.309	.305	.354	.357
Horsepower		1.08	1.05	1.37	1.34	1.66	1.63	1.92	1.90
Ton per horsepower-hour		.173	.174	.183	.177	.187	.187	.184	.188

A similar test of discharge openings of the ball mill was given in a former paper.[2] There the results of the ball-mill test at 80 per cent. speed showed about the same degree of failure in efficiency as the present rod-mill tests at 70 per cent. speed. At very slow speeds the ball mill seemed to function better than the rod mill at similarly slow speeds. The rod mill, like the ball mill, gave higher capacities when the discharge openings were large. The range of satisfactory speeds of the rod mill was more limited than that of the ball mill. The rod-mill work shown in *Table* 8 was best with the large discharge because less ore was retained in the mill. In regular mills the large opening required to facilitate the addition and removal of rods seems to have been an advantage not recognised when the first mills were built.

(*To be continued.*)

[2] GOW, A. M., GUGGENHEIM, M., CAMPBELL, A. B., and COGHILL, W. H. *Ball Milling Am. Inst. Min. & Met. Eng.*, Tech. Pub., 517, 1934.

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